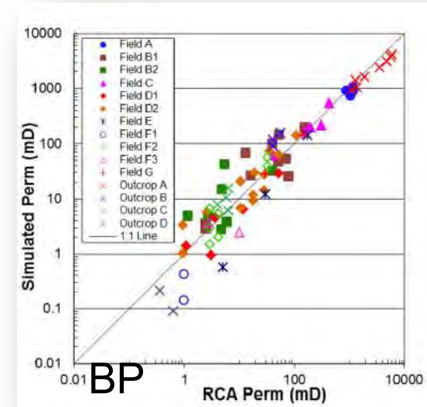
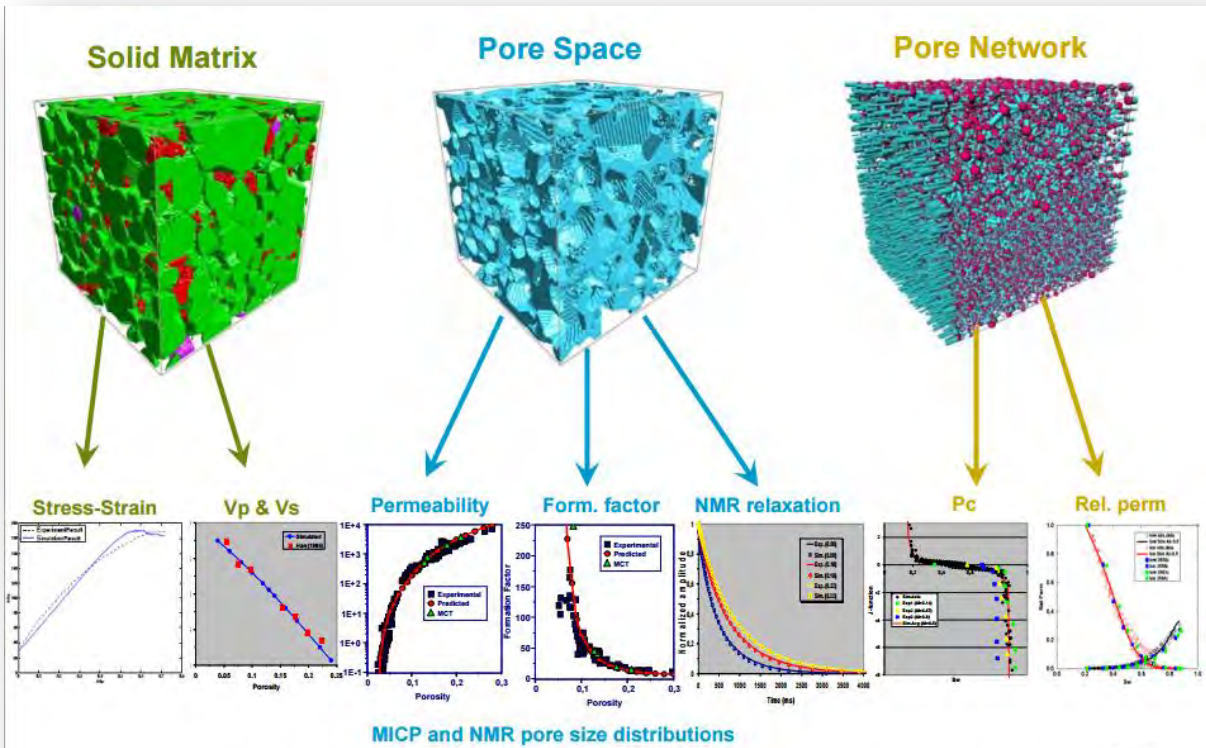
Introduction to
Digital Rock Physics and Predictive Rock Properties

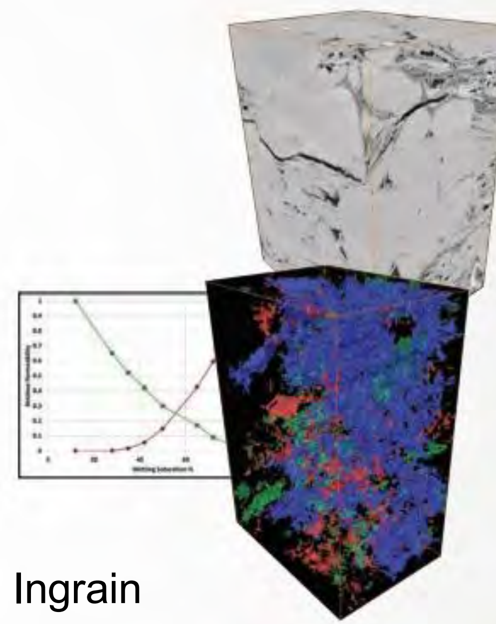
Mike Marsh, Ph.D.
Carl Zeiss Microscopy

Shawn Zhang, Ph.D.
DigiM Solutions





Numerical Rocks (FEI-Lithicon)



Ingrain

What is Digital Rock Physics?

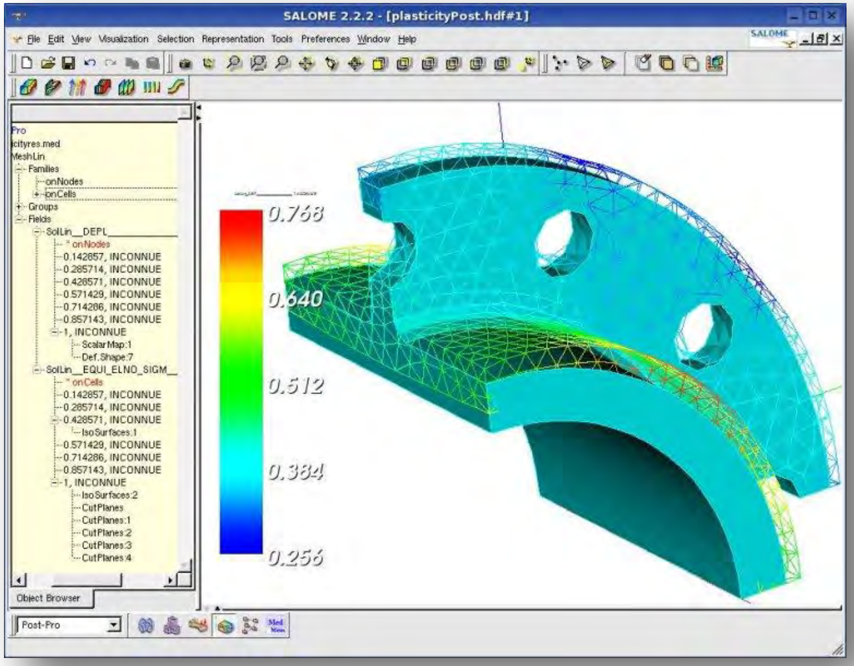
- Application of ***Numerical Modeling*** to rock properties
- Digital Rocks **IS NOT** Digital Image Analysis
  - Porosity
  - Digital petrography and granulometry
  - Fracture mapping and analysis
  - Bedding analysis
  - Mineralogy
  - Bioturbation analysis
- Digital Rocks **IS** simulation of rock physics
  - Fluid transport (Stokes equations)
  - Electrical conductivity (Ohm's law)
  - Diffusion (Ficke's second law)
  - …

Introduction to Numerical Modeling

Numerical modeling is a mainstay of engineering

- Computer-aided Engineering (CAE)
- General-purpose CAE Tools (not exhaustive)
  - Ansys CFD
  - Abaqus
  - COMSOL Multiphysics
  - Exa
  - Nastran
  - OpenFOAM
  - …many, many more

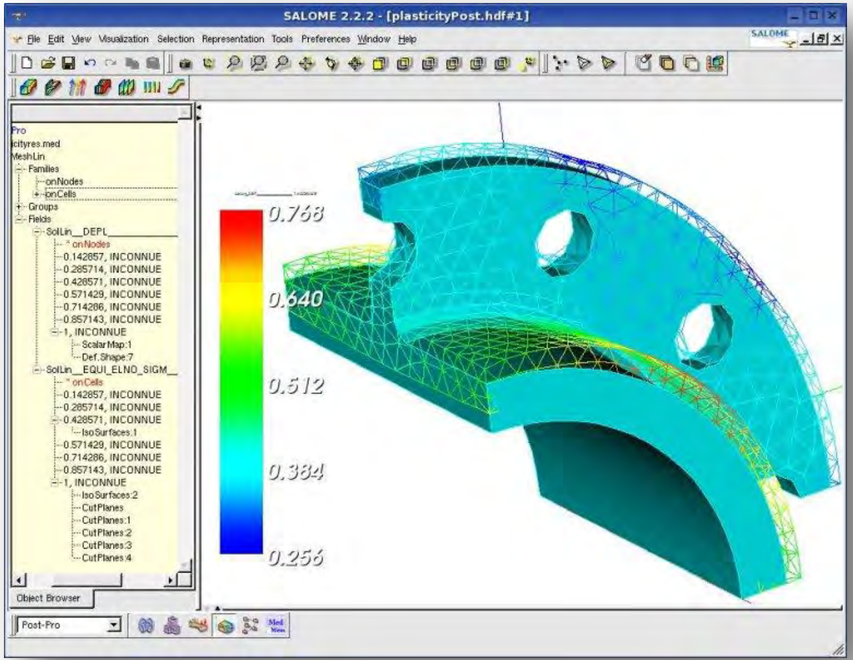
Mainstay of Reservoir Engineering
- Dynamic Reservoir Modeling Tools



Nonlinear static analysis of a 3D structure subjected to plastic deformations

Solving physics by simulation

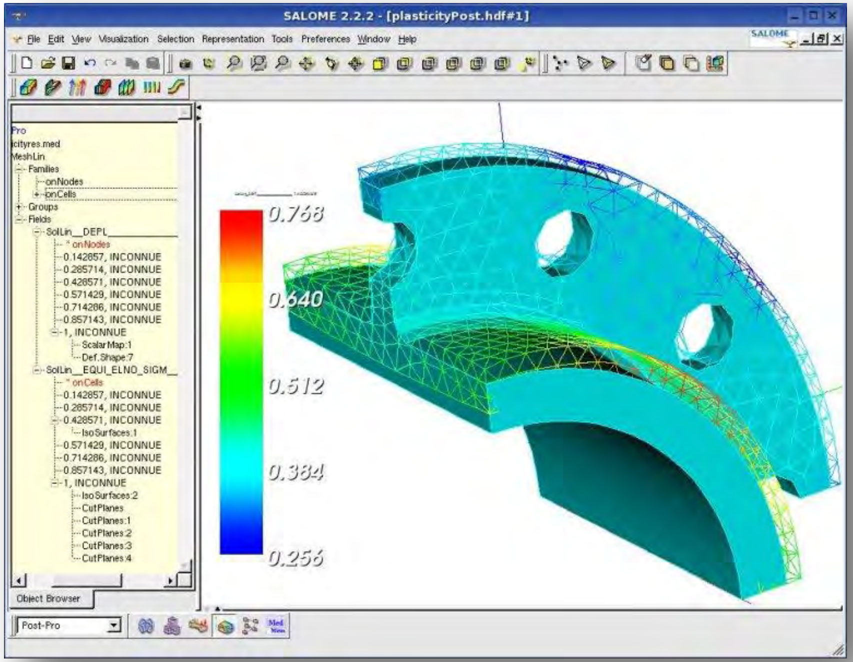
- Construct a model
  - Discretize a spatial domain
- Constrain with boundary conditions
  - Interface behavior
  - Initial values
- Use a compute engine and a numerical scheme to integrate differential equations for physics of interest
- Iterate until some convergence criterion is satisfied



Nonlinear static analysis of a 3D structure subjected to plastic deformations

Solving physics by simulation

- Where does the model come from?
  - Traditional CAE:
    Engineer drafts a model
  - Digital Rocks:
    Model is derived from an image
- CAD-based
  - Engineering draws a picture of the spatial domain
  - Limited to simple human-engineered domains
- Image-to-simulation
  - Directly image a material
    - Natural materials
      - » Bones, rocks
    - Manmade materials
      - » Foams, composites
  - Segment image into discrete phases
    (e.g. pore and matrix)
  - Convert segmentation into spatial model
  - Result is **sensitive to imaging and segmentation accuracy**
    (difficult to assess, but see DRP benchmarks paper)



Nonlinear static analysis of a 3D structure subjected to plastic deformations

Diverse Expertise Required for Digital Rocks

Imaging

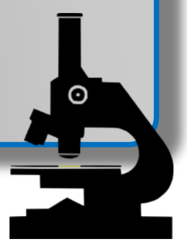
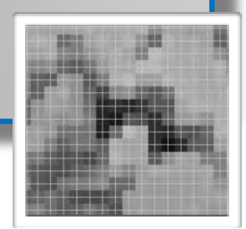
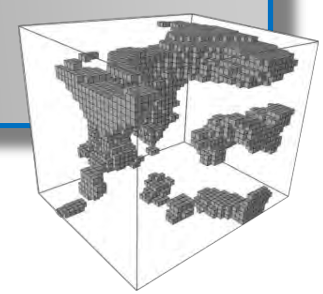


Image Processing



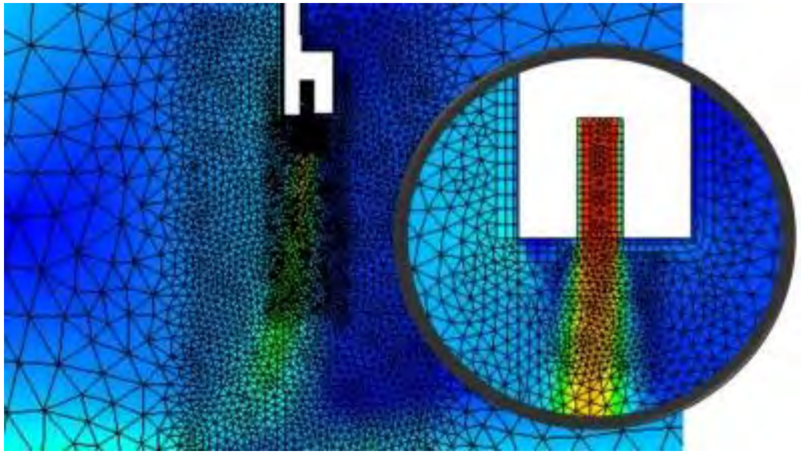
Numerical Modeling



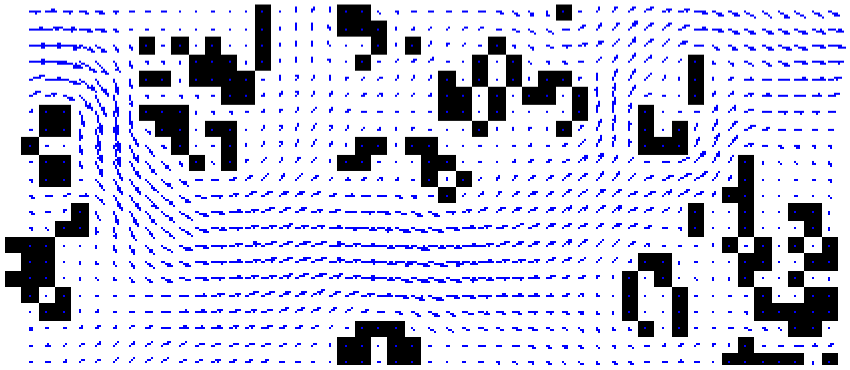
Geological Interpretation and Application

Spatial discretization

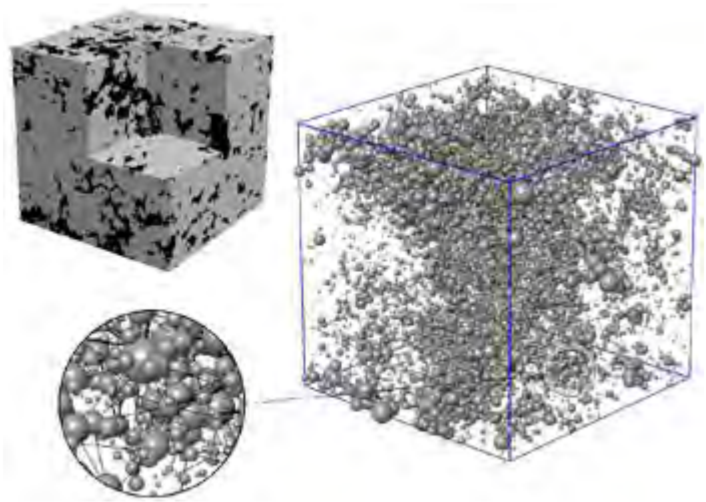
- Unstructured polyhedral meshes
  - Uniform or Adaptive Mesh Refinment
- Lattice models
- Pore network models



Autodesk website

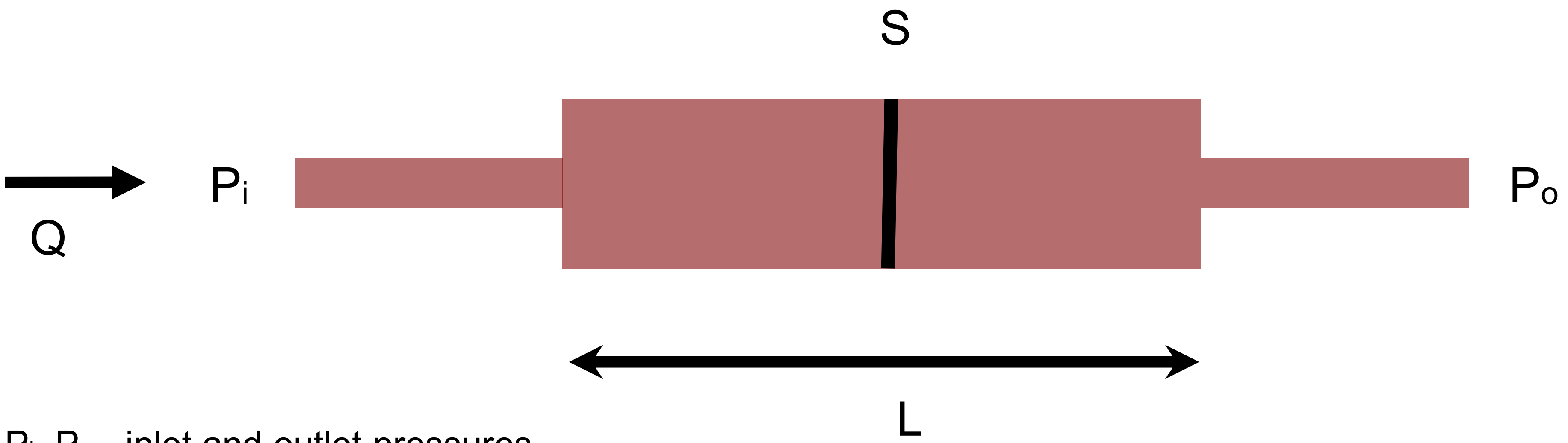


exolete website



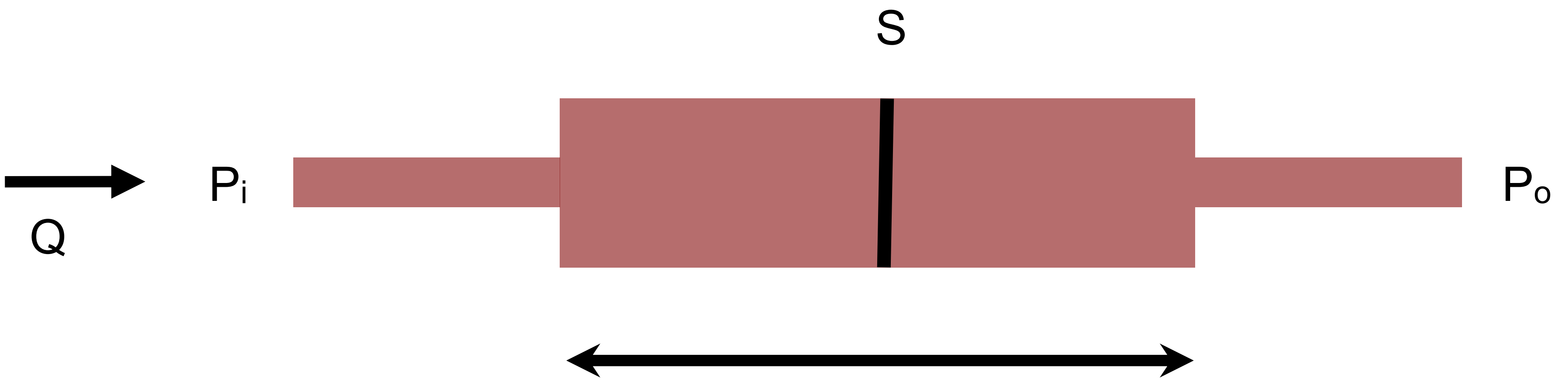
PoreSim website

Flow modeling - Geometry



P_i, P_o - inlet and outlet pressures
Q is the flow rate
L is the length of the porous medium
S is the cross section

Flow modeling – Darcy's Law

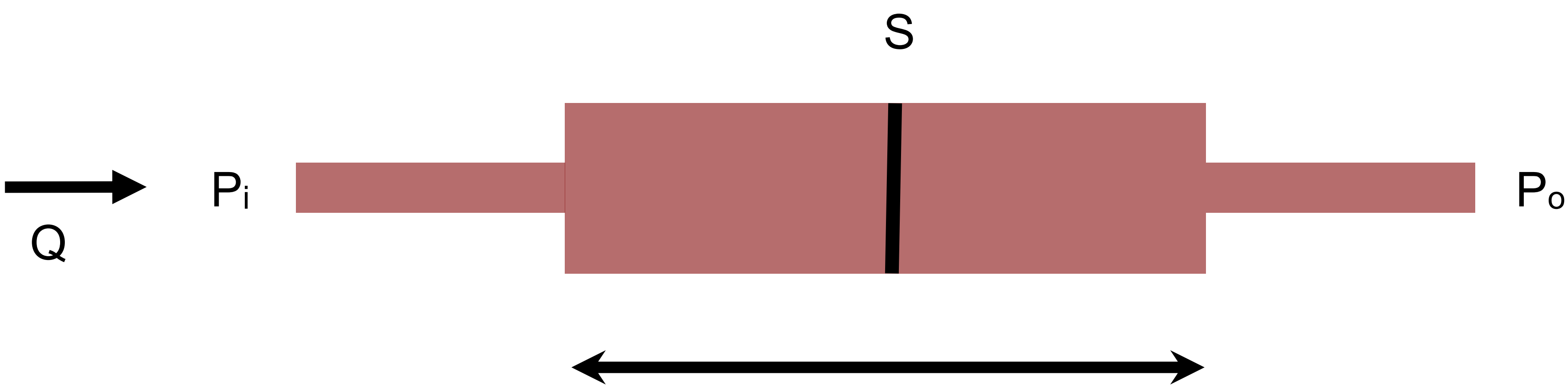


$$\frac{Q}{S} = -\frac{k}{\mu}\frac{\Delta P}{L}$$

μ is the dynamic viscosity of the fluid

k is the permeability

Flow modeling – Darcy's Law
Stokes equations can be solved to give you the pressure drop



$$\frac{Q}{S} = -\frac{k}{\mu}\frac{\Delta P}{L}$$

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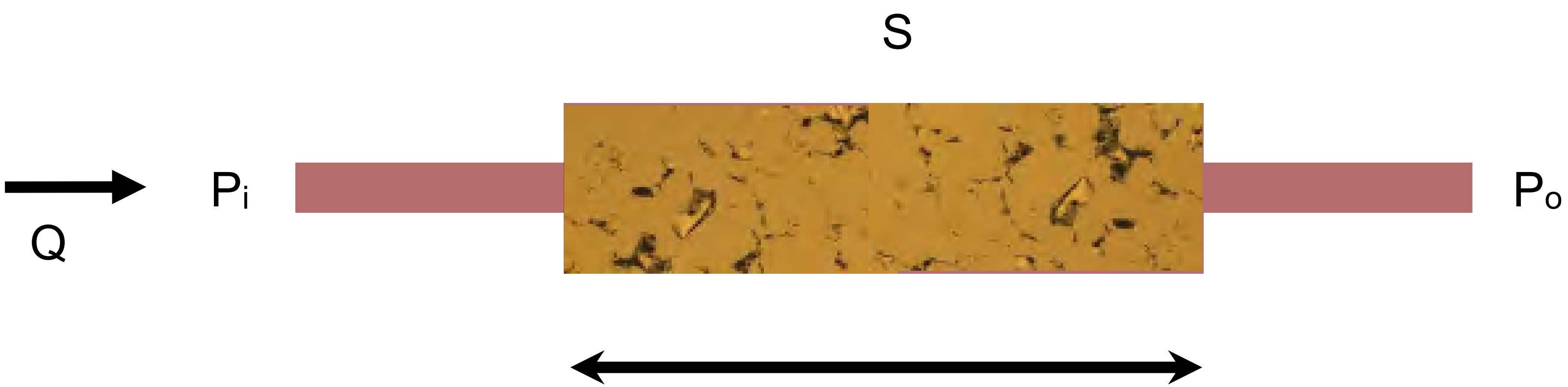
k is the permeability

$$\begin{cases} \vec{\nabla}.\vec{V} = 0 \\ \mu\nabla^2\vec{V} - \vec{\nabla}P = \vec{0} \end{cases}$$

Flow modeling – Darcy's Law

Image-derived model captures pore space geometry



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Flow modeling – Darcy's Law

Boundary conditions constrain the simulation

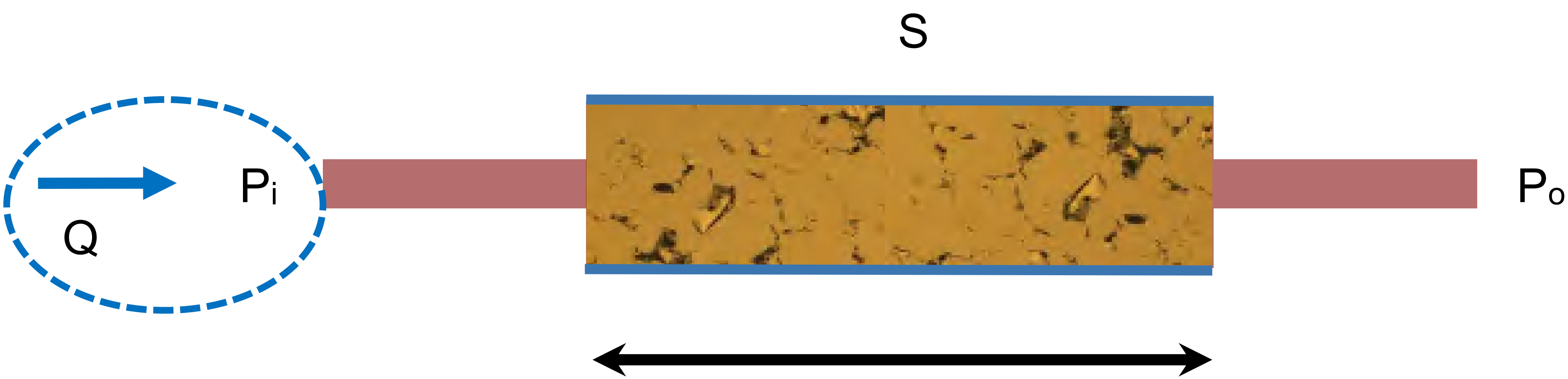

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Figure 1 Berea sandstone.

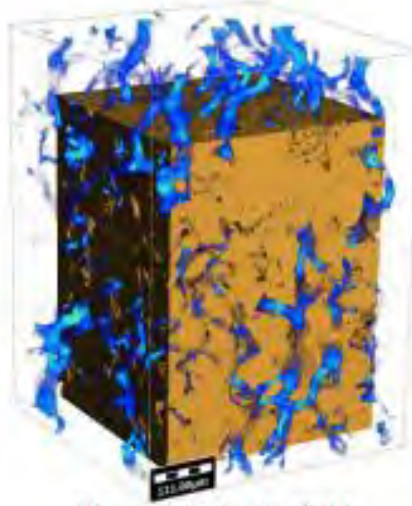

Figure 2 Velocity field.

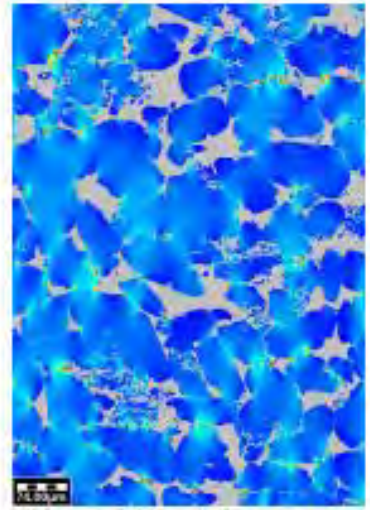

Figure 3 Von Mises stress.

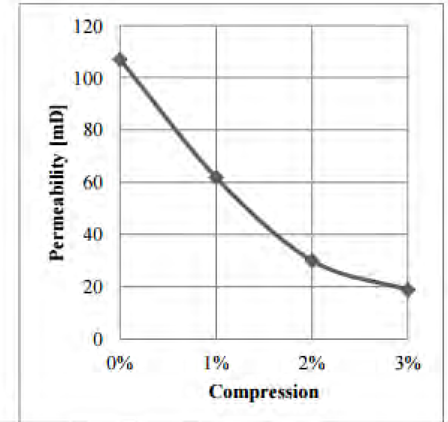

Figure 4 Brine saturation with 60%, 40% and 20%. Air intru

SCA2014-057 1/6

AN INTEGRATED APPROACH TO COMPUTE PHYSICAL PROPERTIES OF CORE SAMPLES

S. Linden[1,2], T. Cvjetkovic[2], E. Glatt[2] and A. Wiegmann[2]
[1]Fraunhofer ITWM, Fraunhofer-Platz 1, 67665 Kaiserslautern, Germany
[2]Math2Market GmbH, Trippstadter Str. 110, 67663 Kaiserslautern, Germany

Tradeoffs between Compute Time and Domain Size

Different strategies for encoding the spatial domain capture different

Tradeoff

- Size of the domain (more representative results)
- Precision of the geometry (more accurate results)

Bigger domain
Compromised geometry

Precise geometry
Smaller domain

Pore network modeling
iRock, Lithicon, PoreSim, IFP

Lattice Boltzmann
Ingrain, Exa

Irregular Mesh
Ansys/Fluent
COMSOL Multiphysics

Pixel FVM
GeoDict, Xlab-Hydro, Simpleware, Volume Graphic
Academic FVM solvers

Compute strategies

Can I have both: precise geometry AND big domains?

- Shared memory machines (expensive, but easy to program)
- Beowulf clusters (cheap, but difficult to program)
- GPU clusters (difficult to program, difficult to scale)

Method	S-FFT	LIR	EJ-diff	EJ-cond	LS
Runtime [h]	26.4	14	10.9	11	22.6
Memory [GB]	40.5	5.8	10.6	10.6	97.1

Table 2 Runtime and memory requirements of the PDE solvers. The runtimes include three load cases for S-FFT, LIR, EJ and six load cases for the LS solver.

Linden et al. SCA 2014-057

Advantages and Disadvantages relative to lab experiments

- Advantage: Speed
  - Faster than lab experiments – consider SCAL on shales
- Disadvantage: REV
  - Imaged and modeled volume may not be representative and far smaller than domain of corresponding lab experiment
- Advantage: Perform experiments that are difficult to do
  - No real-world apparatus required
  - Repeat experiments under different boundary conditions

Landscape of DRP: Academic Efforts

- ANU/UNSW (Digital Core Consortium)
- ETH
- IFP
- Imperial College (Consortium on Pore Scale Modeling)
- Heriot Watt
- LSU (PoreSim Consortium)
- Stony Brook University
- University of Wyoming
- University of of Texas

Business Models in Digital Rock Physics

DRP as part of a Research Contract

Research contracts may address an open problem related to reservoir characterization or production. Sometimes, service providers may use DRP simulation engines as part of their effort to fulfil such contracts

DRP: Simulation as a Service

Service providers may offer a DRP simulation service, whereby customers can provide rocks which must be imaged (or existing images) and the service provider will execute a DRP simulation and provide the results to the customer.

DRP: Simulation Software installed on End-user Computer

Software vendors may sell software licenses for applications that end-users can install on their own hardware, whereby those end-users can execute the DRP simulations at any time on any digital image.

Additional Reading

Digital Rocks: Developing an Emerging Technology Through to a Proven Capability Deployed in the Business

Fredrich et al. 2014 (SPE-170752-MS)
SPE ATCE 2014

Digital rock physics benchmarks—Part I: Imaging and segmentation

Andrae et al. 2013
Computers and Geoscience

Digital rock physics benchmarks—Part II: Computing effective properties

Andrae et al. 2013
Computers and Geoscience

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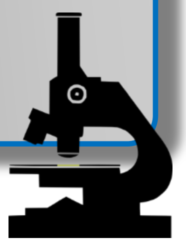
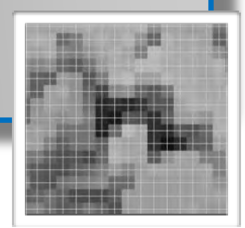
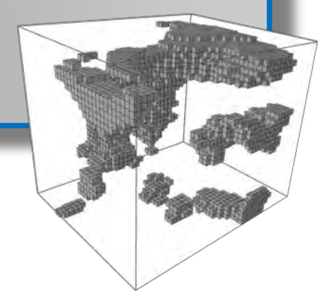


Image Processing



Numerical Modeling



Geological Interpretation and Application

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We make it visible.